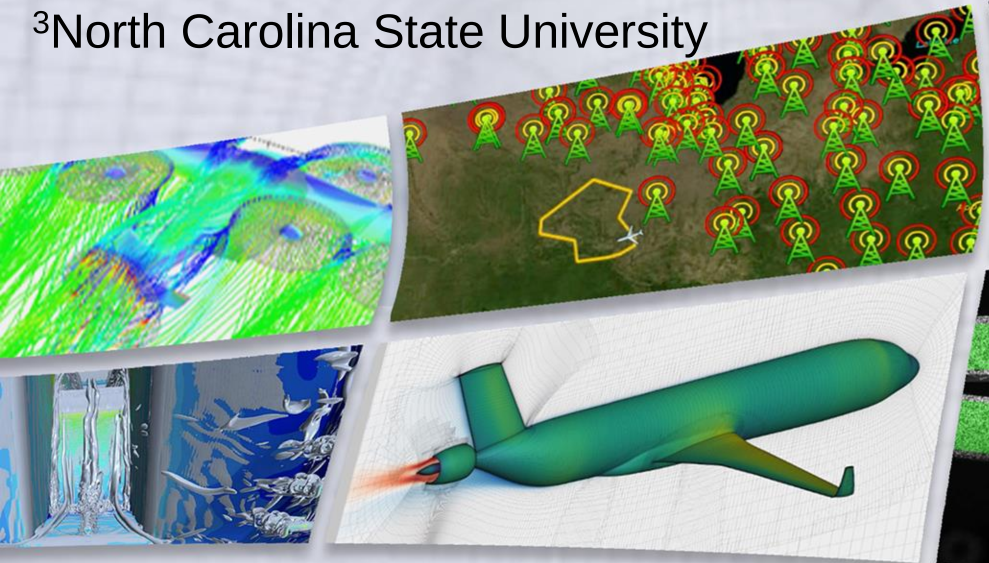
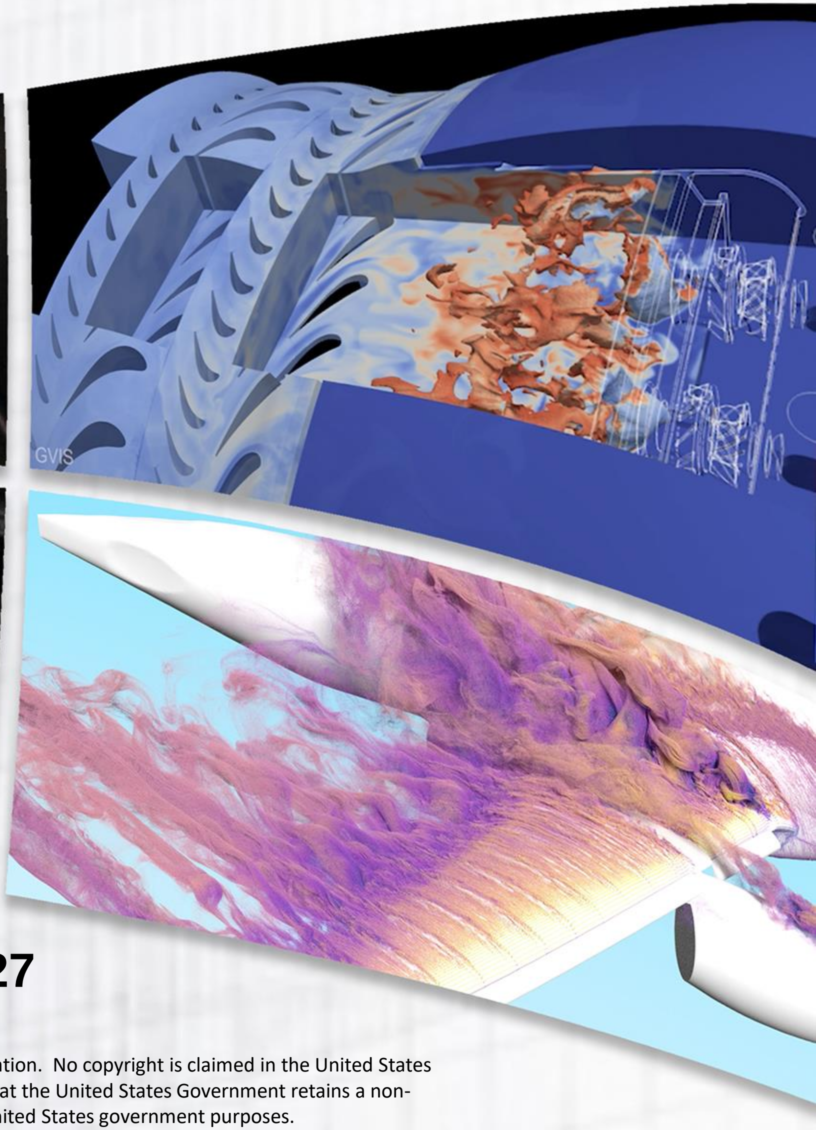
National Aeronautics and Space Administration

Predicting Fiber Breakage Failure of Plain Weave Fabric with Multiscale Recursive Micromechanics

Brandon L. Hearley[1], Evan J. Pineda[1], Brett A. Bednarcyk[1],
Scott M. Murman[2], Mark Pankow[3]
[1]NASA Glenn Research Center
[2]NASA Ames Research Center
[3]North Carolina State University





Innovative solutions through foundational research and cross-cutting tools

2023 AIAA SciTech Forum, January 23-27

www.nasa.gov

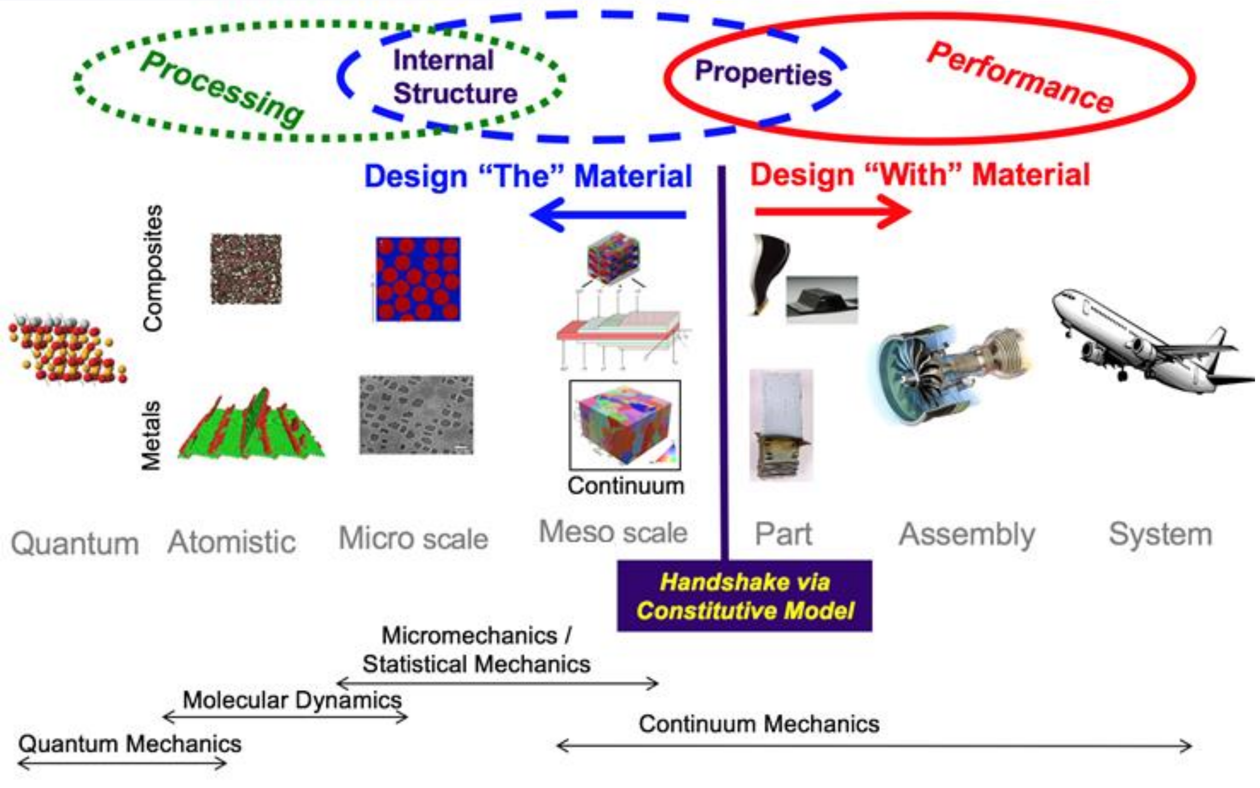
Outline

1. Motivation and Overview Simulating Fabric Behavior in NASMAT
2. Failure Theory
   - Determining critical parameters
   - Implementation in NASMAT
3. Verification / Simulation Results
4. Parameter Sensitivity Study
5. Conclusion/Summary

Motivation: ICME

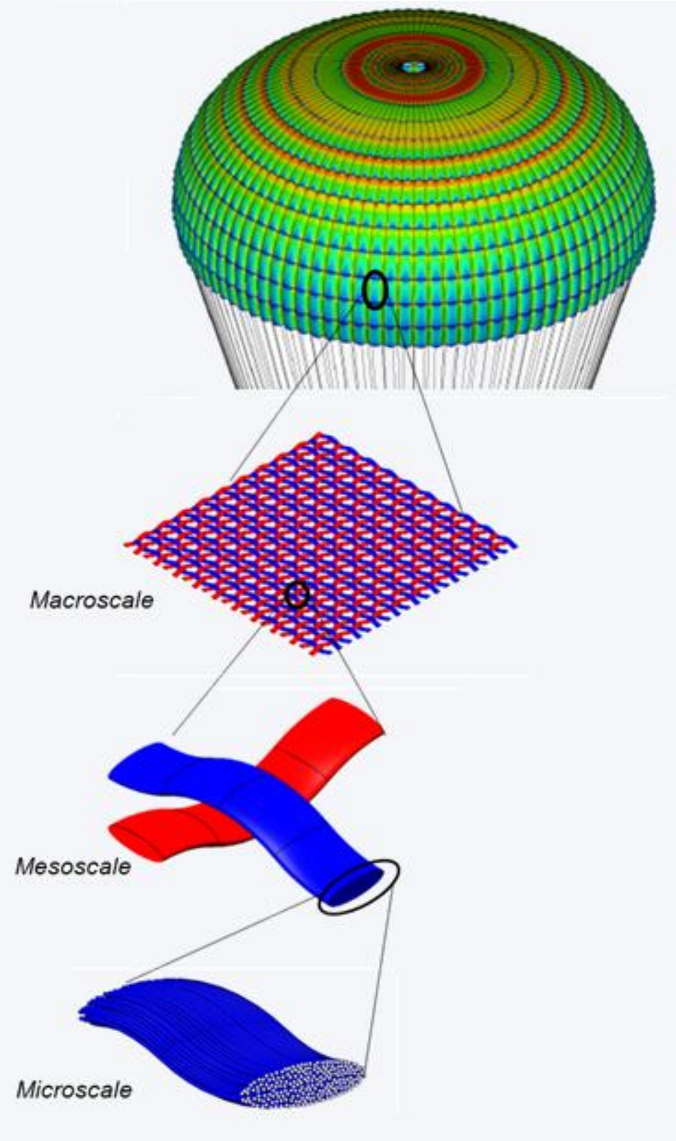
- **Integrated Computational Material Engineering (ICME)** aims to reduce the time and improve the performance of new products through **"fit-for-purpose"** materials
  - Requires interaction between the "Design with the Material" and "Design the Material" paradigms

- Efficient software tools that can pass information across various length scales are necessary to enable ICME



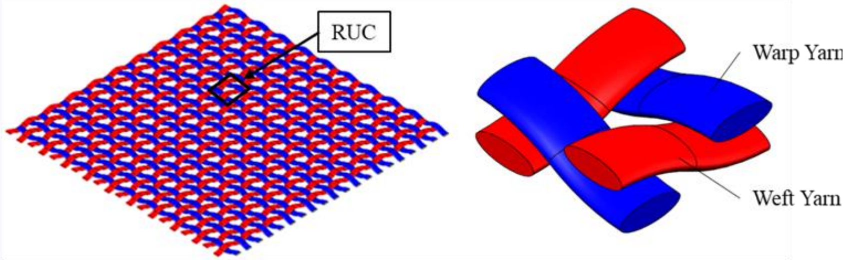
Motivation

- Unreinforced fabrics used in a wide variety of high-performance applications
- Fabrics are multiscaled and inherently complex
  - Microscale – Individual filaments
  - Mesoscale – Yarn bundles
  - Macroscale – Overall fabric
- Ability to design “fit-for-purpose” materials requires efficient simulation tools that can capture mechanisms at each scale
  - Current analysis relies heavily on legacy data – same materials used consistently

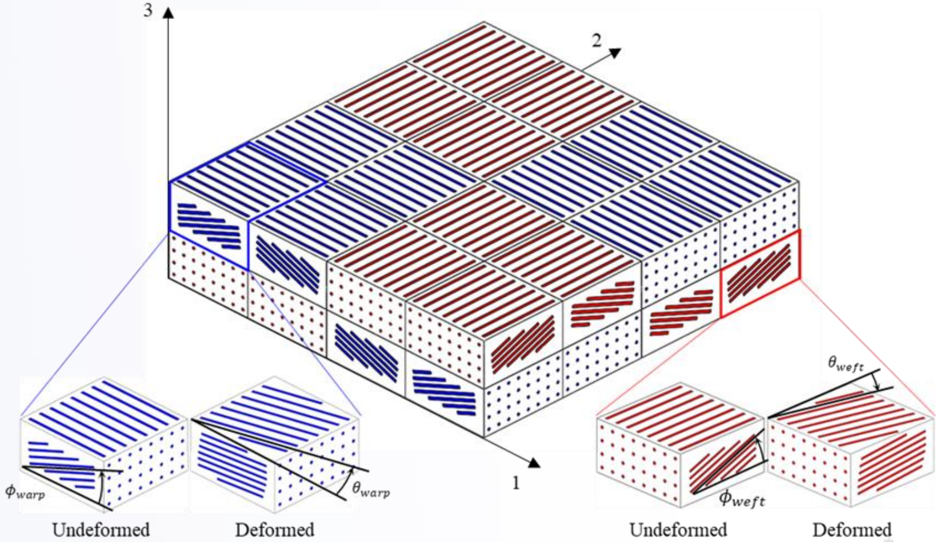


Simulating Fabric Behavior in NASMAT

- NASA's Multiscale Analysis Tool (NASMAT)
  - Multiscale analysis tool that uses Repeating Unit Cell (RUC) analysis and Generalized Method of Cells (GMC) micromechanics
  - Typically used for reinforced composite analysis
- Previous work: Modified NASMAT to predict unreinforced fabric behavior
  - Allow the tow geometry to change with applied loading
  - Add the mechanics that govern tow deformation in a predictive manner
- **Current work**: Add the capability to predict fiber breakage failure



Fabric structure and repeating volume element

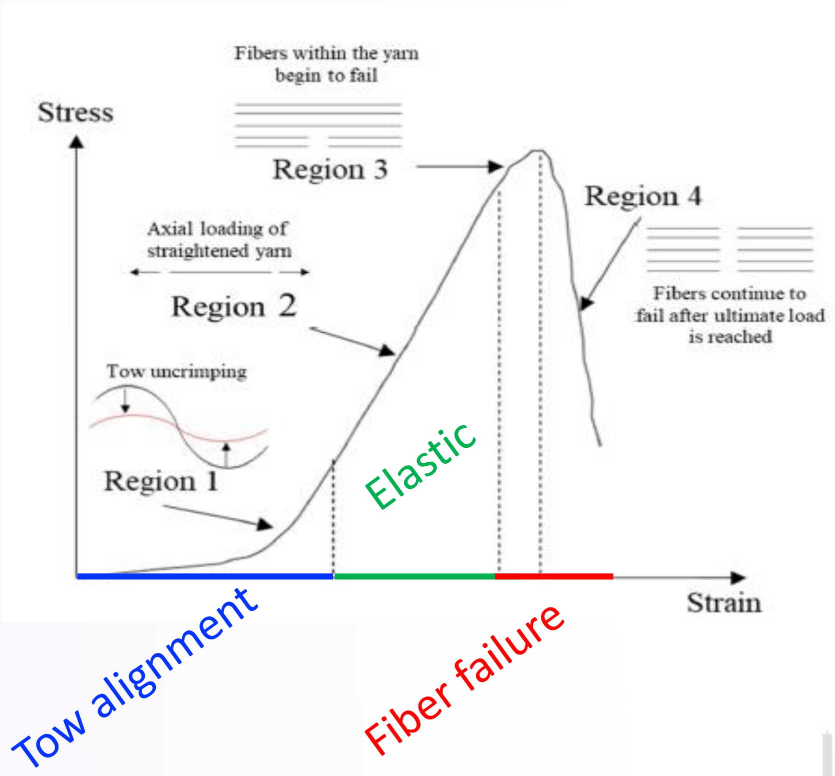


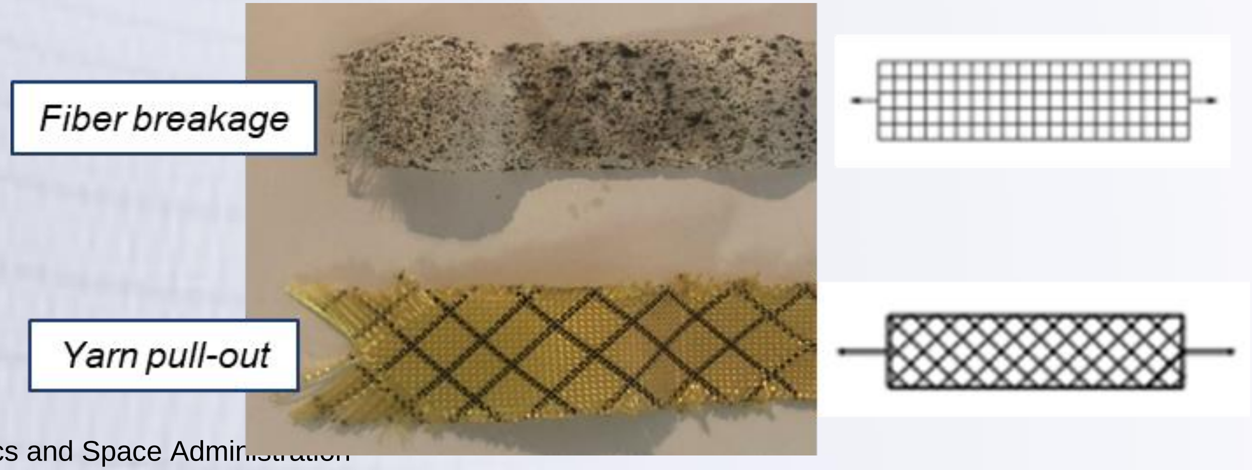
Fabric RUC with defining angles

Woven Fabric Failure Modes

- Failure Modes
  - Fiber breakage
    - Tow-aligned loading
    - Individual fibers within the tow fail progressively with applied loading
  - Yarn pull-out
    - Tows slip relative to one another at the cross-over points
    - Off-axis loading

Macroscale behavior of fabric under tow-aligned loading





Fiber Breakage Failure Theory

- Microscale fibers in each subcell fail according to a Weibull Distribution

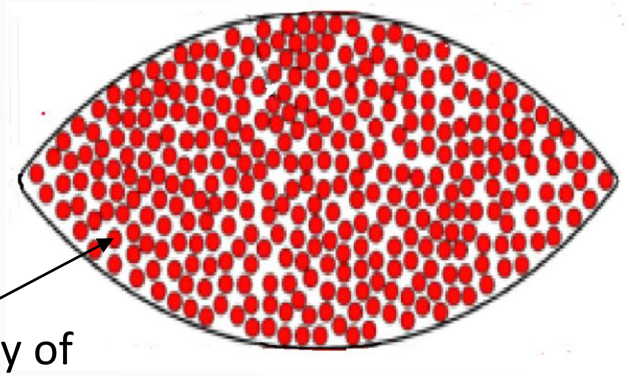
$$F(\sigma) = 1 - \exp\left(-l_c \alpha \sigma^{\beta}\right)$$

$$\alpha = scale\ parameter$$

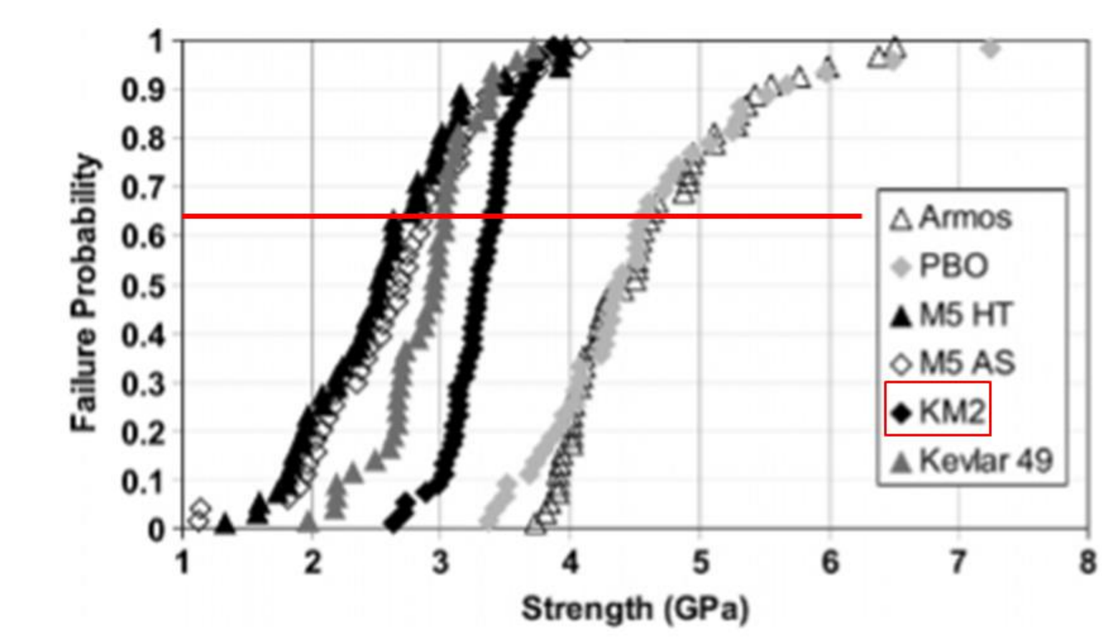
$$\beta = shape\ parameter$$

$$l_c = critical\ fiber\ length$$

- Shape and scale parameters found from single fiber tension tests
  - Scale: Strength at which 63.2% of fibers have failed
  - Shape: Slope



Calculate probability of failure for each fiber



Cumulative probability of failure for single fiber tension test[1]

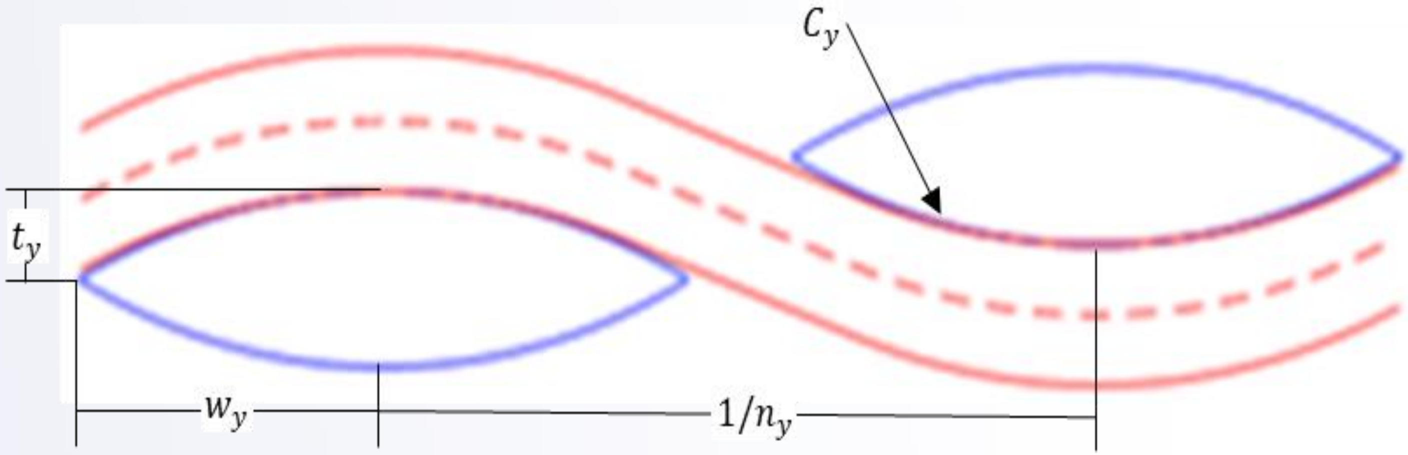
[1]Leal, A.A., Deitzel, J.M., and Gillespie, John W. Jr., "Assessment of compressive properties of high performance organic fibers," *Composites Science and Technology,* Vol. 67, 2007,, pp. 2786-2794.

Finding the Critical Fiber Length

- Critical fiber length accounts for non-uniform load distribution between surviving fibers
  - Found from the mesoscale yarn geometry, Weibull parameters, and the shear resistance of the contact area between yarns[1]

$$l_c = \left[\frac{1}{C_y n_y \boldsymbol{\tau_y}}\left(\frac{4}{3}\alpha\right)^{-\frac{1}{\beta}}\Gamma\left(1+\frac{1}{\beta}\right)\right]^{\frac{\beta}{1+\beta}}$$

$$\Gamma(z) = \int_0^\infty x^{z-1}e^{-x}dx$$



[1]N. Pan, "Analysis of woven fabric strengths: prediction of fabric strength under uniaxial and biaxial extensions," Composite Science and Technology, vol. 56, pp. 311-327, 1996.

Contact Area Shear Resistance τ_y

- Two components to contact area shear resistance

$$\boldsymbol{\tau_y} = \boldsymbol{\tau_{y1}} + \boldsymbol{\tau_{y2}}$$

- Pressure-related term τ_{y1} (active under tensile loading)

$$\boldsymbol{\tau_{y1}} = \frac{\mu P}{C_y}$$

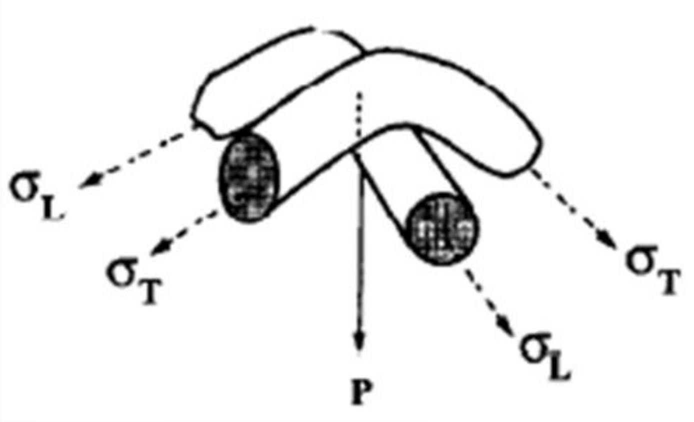
$\mu =$ friction coefficient

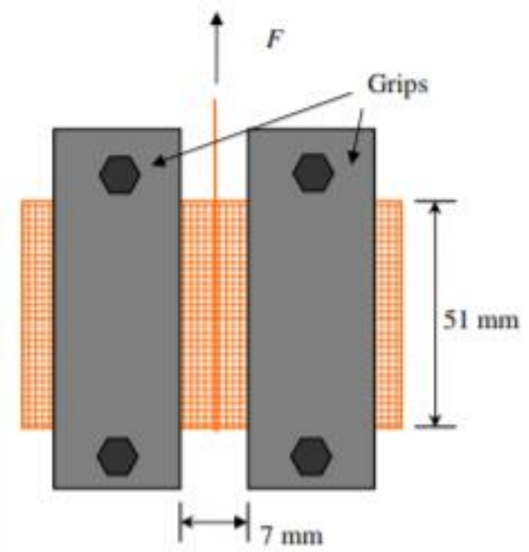
$P =$ Cross-over pressure

$$P = (2\sigma_T \sin\phi_T + 2\sigma_L \sin\phi_L)$$

- Pressure-independent term τ_{y2} (*in-situ* residual shear)
  - Determined from single yarn pullout tests

$$\boldsymbol{\tau_{y2}} = \frac{F\rho}{Int(n_y L) w_y \tanh(\rho w_y)} \qquad \rho = \frac{1}{t_y}\sqrt{\frac{G_y}{\pi E_y}}$$





Single Yarn Pullout Test Schematic

Failure Theory Implementation

- Implementation in NASMAT
  - At each load step, loop through the total number of fibers N_f in each subcell to determine number of surviving fibers through random number comparison with the probability $F(\sigma_{ii}^L)$
  - Define a surviving fiber ratio (Ψ) and modify the subcell stiffness ($C_{undamaged}$)

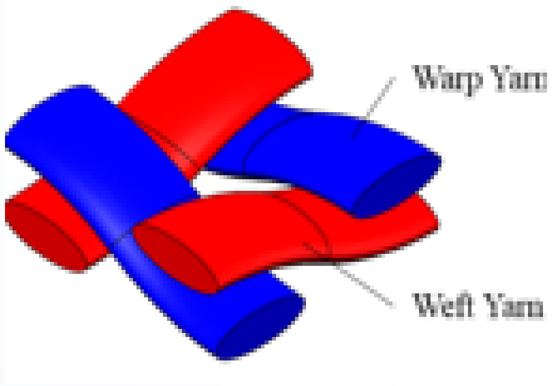
$$\Psi = \frac{N_f - N_{fail}}{N_f} \qquad C = \Psi C_{undamaged}$$

  - Methodology introduces randomness into the calculation → able to capture the stochastic nature observed experimentally

Material Parameters for Failure Simulation

- Material Parameters independent obtained
  - Predicted behavior and failure of a Kevlar K706 plain weave subject to warp-aligned and weft-aligned uniaxial loading
  - Weibull parameters provided from Nilakanten et al.[1]
  - Single yarn pullout results and friction coefficient provided from Dong et al.[2]

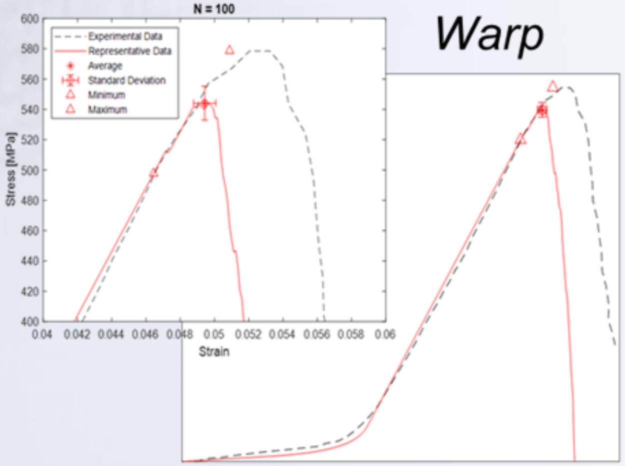
Parameter	Warp	Weft
Scale (α) [MPa]	3323.0	3700.4
Shape (β) [-]	18.0023	24.8803
Pressure-independent shear resistance (τ_{y2}) [MPa]	1.53	0.72

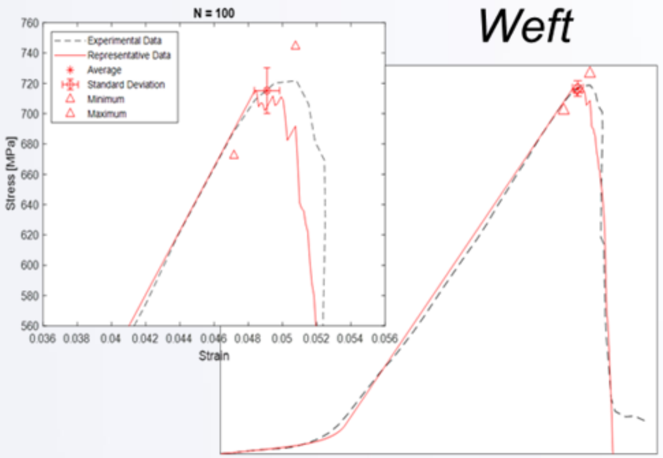


[1]G. Nilakantan and J. W. Gillespie Jr., "Ballistic impact modeling of woven fabrics considering yarn strength, friction, projectile impact location, and fabric boundary condition effects," Composite Structures, vol. 94, no. 12, pp. 3624-3634, 2012.
[2]Z. Dong and C. T. Sun, "Testing and modeling of yarn pull-out in plain woven Kevlar fabrics," Composites: Part A, vol. 40, pp. 1863-1869, 2009.

Verification of Failure Behavior with Experimental Data

- Performed 100 simulations of each load case in NASMAT
  - Implementation allows for variation in results for the same run case





Yarn	Simulation		Experimental
	Average Ultimate Stress [MPa]	Standard Deviation [MPa]	Ultimate Stress [MPa]
Warp	544.18	11.2	578.51
Weft	715.19	15.1	721.77

- Parameters sufficient in providing good agreement with experimental data

Challenges for Practical Implementation

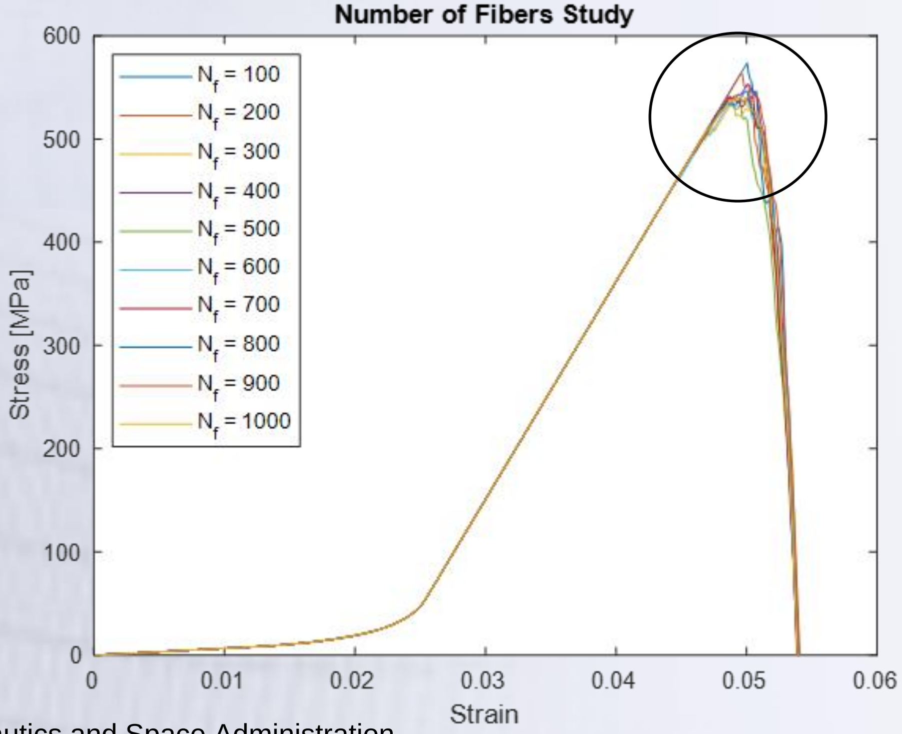
- In early design stages (material selection) or designing "fit-for-purpose" material, some inputs may be difficult to obtain
  - Yarn material properties
  - Yarn mesoscale geometry
  - **Yarn microscale geometry (# of fibers)**
  - Fiber tension test results – Weibull Parameters
  - **Yarn pullout test results – Contact area shear resistance**

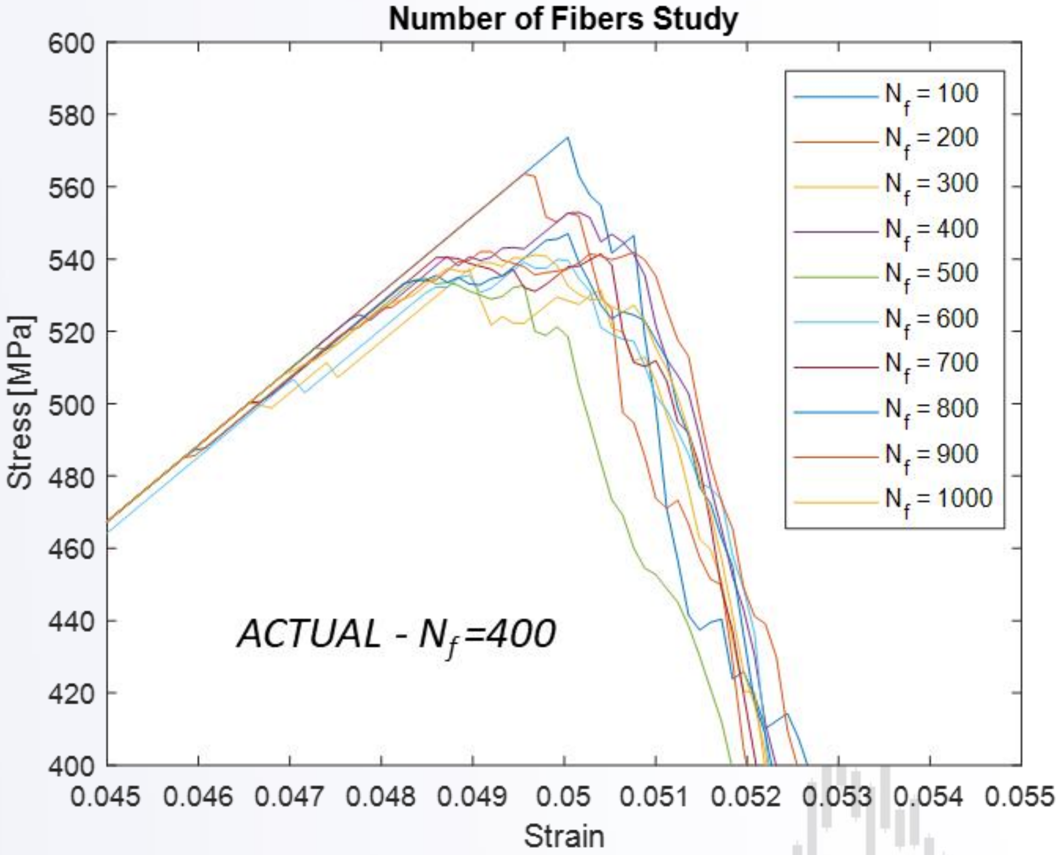
- Performed Parameter Sensitivity studies to determine importance

Parameter Sensitivity Study: Number of Fibers

- Performed simulations using the same input parameters while varying the total number of fibers in a tow
  - Not randomly seeded – same N_f will give same result each run

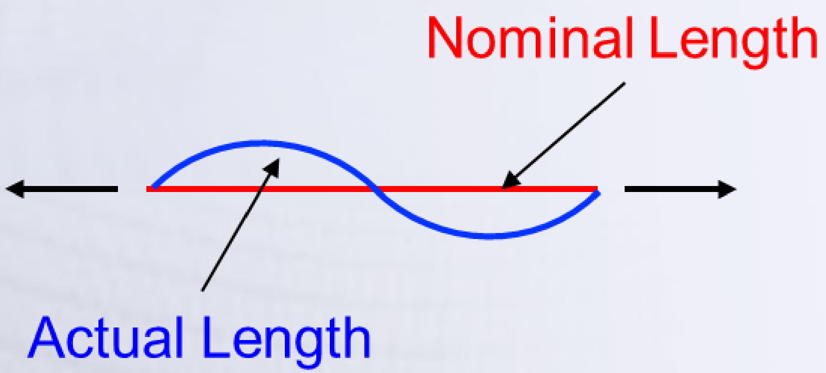
$$\Psi = \frac{N_f - N_{fail}}{N_f} \qquad C = \Psi C_{undamaged}$$





Parameter Sensitivity Study: Critical Fiber Length

- Study overprediction in load for different lengths
  - Nominal Length – Length of the sample (100 mm)
  - Actual Length – Length of the nominal tow path (takes into account the tow undulation)
  - Critical Length – Solved sub-fiber critical length

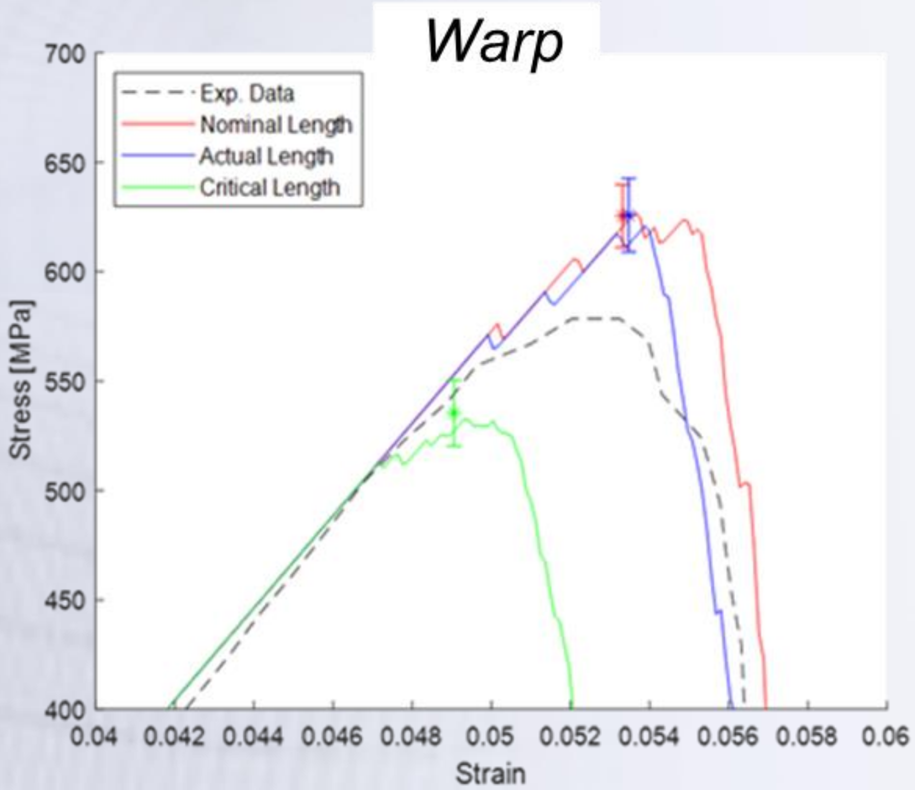


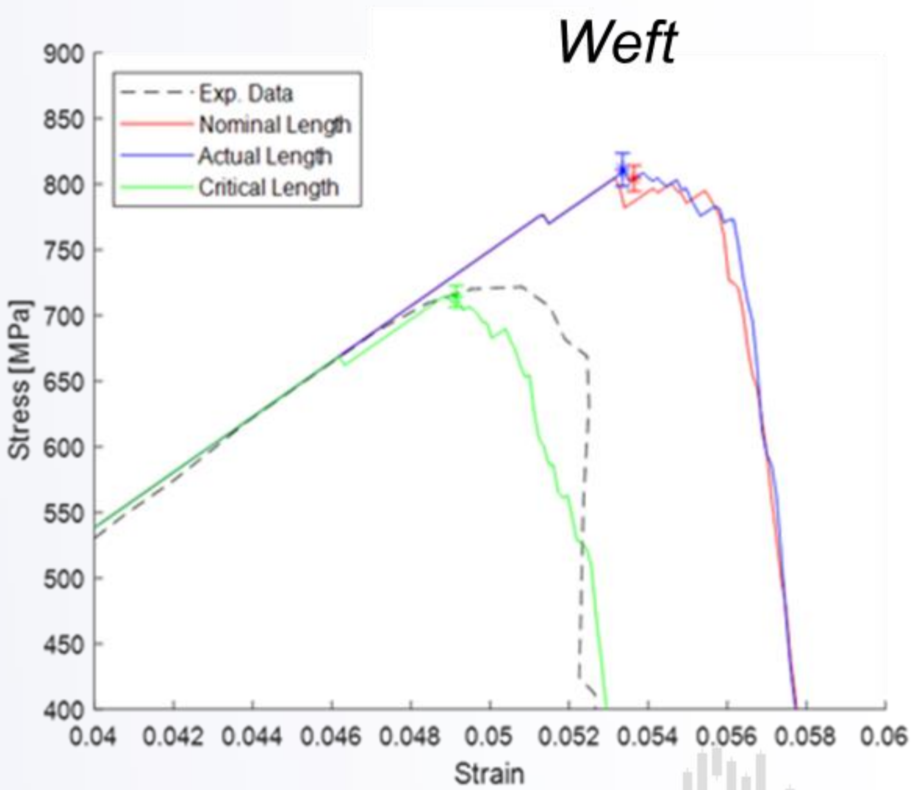
$$F(\sigma) = 1 - \exp\left(-\boldsymbol{l_c}\alpha\sigma^{\beta}\right)$$

$$\boldsymbol{l_c} = \left[\frac{1}{C_y n_y \tau_y}\left(\frac{4}{3}\alpha\right)^{-\frac{1}{\beta}}\Gamma\left(1+\frac{1}{\beta}\right)\right]^{\frac{\beta}{1+\beta}}$$

Parameter Sensitivity Study: Critical Fiber Length

- Performed 100 simulations for both warp and weft aligned tension for each length case
  - Randomly seeded each run to study variations observed





Conclusion/Summary

- Introduce Weibull Distributions into the fabric failure theory for the fiber breakage failure mode at the microscale
  - Implemented the failure theory into NASA's existing multiscale analysis tool (NASMAT)
- Able to predict macroscale fabric failure behavior in NASMAT for tow-aligned loading
  - Verified behavior for warp and weft aligned load cases for Kevlar K706 plain weave
- Determined relative importance of the input parameters to aid initial design stages when selecting/designing fabric materials
- Allows designers to make reasonable approximations when designing new "fit-for-purpose" materials
  - Enables ICME by providing tools that can replace the dependence on legacy data

Thank You for Your Attention

Acknowledgements

The authors would like to thank

- NASA Space Technology Mission Directorate (STMD) Entry Systems Modeling (ESM) project
- Aeronautics Research Mission Directorate (ARMD) Transformational Tools and Technologies project
- Lewis' Educational and Research Collaborative Internship Project (LERCIP) for their support of this work.